(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 March 2003 (20.03.2003)

PCT

(10) International Publication Number
WO 03/023913 A1

(51) International Patent Classification[7]: H01S 3/10, 3/082, G01B 11/02, G01R 33/02, 31/00

(21) International Application Number: PCT/US02/28216

(22) International Filing Date: 5 September 2002 (05.09.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/317,583 6 September 2001 (06.09.2001) US

(71) Applicant (*for all designated States except US*): **BROWN UNIVERSITY RESEARCH FONDATION** [US/US]; 42 Charlesfield Street, Box 1949, Providence, RI 02912 (US).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): **NURMIKKO, Arto, V.** [US/US]; 82 Sargent Avenue, Providence, RI 02906 (US).

(74) Agent: **SMITH, Harry, F.**; Harrington & Smith, LLP, 4 Research Drive, Shelton, CT 06484-6212 (US).

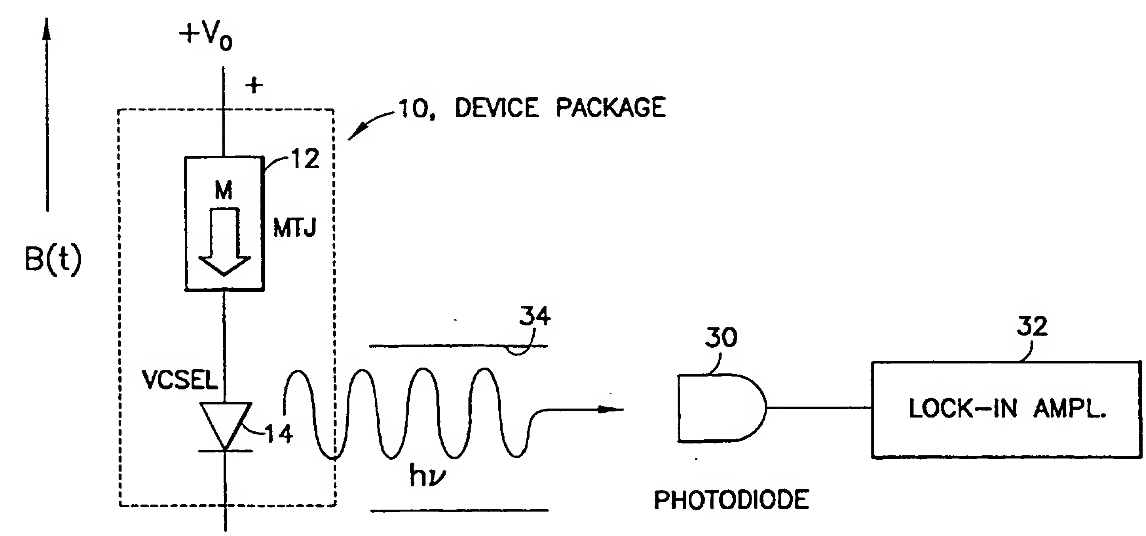
(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

[Continued on next page]

(54) Title: MAGNETO-OPTOELECTRONIC SWITCH AND SENSOR



P_{VCSEL}~3mW; R_{MTJ}~10Ω; ΔR_{MTJ}~3Ω; R_{VCSEL}~300Ω,1−2mA

(57) Abstract: A Magneto-Optoelectronic Device MOD (10) includes a magnetic sensing device (12), such as a magnetoresistive device or a magnetic tunnel junction device, that is combined with a semiconductor light emitter(14), such as a LED or a laser diode, to create a compact integrated device where changes in an ambient magnetic field are expressed as changes in an optical beam intensity emanating from the MOD. Using the MOD (10) the magnetic field related information can be transmitted by a light wave over very large distances through some medium (34), for example, through free space and/or through an optical fiber.

WO 03/023913 A1

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

MAGNETO-OPTOELECTRONIC SWITCH AND SENSOR

STATEMENT OF GOVERNMENT RIGHTS:

This invention was made with Government support under Army Research Office Grant 530-1617-03. The Government has certain rights in this invention.

TECHNICAL FIELD:

These teachings relate generally to magnetic field sensing devices, and more specifically relate to an integrated circuit embodiment of a magnetic field sensor, such as a Magnetic Tunnel Junction (MTJ) sensor device whose output signal is used to modulate the optical output of a light emitting device, such as a Light Emitting Diode (LED) or a laser diode, such as Vertical Cavity Surface Emitting Laser (VCSEL).

BACKGROUND:

The ability to remotely sense magnetic fields without direct physical presence or contact with the field location is important in many applications. These applications include the measurement of magnetic field changes in a difficult or hostile environment (such as earthquake warning or battlefield sensing, which are usually performed by a magnetometer in close physical proximity), or the sensing of information in a magnetic storage medium (as usually performed by a flying head of a computer hard disk drive). Another important application involves contactless sensing of current pulses on a microelectronic chip, especially the submicron scale interconnect lines used to wire the various parts of a chip together, and which limit the speed of the operation of the chip. The present methods for sensing and/or measuring magnetic fields, whether on a macroscale or a microscale, make telemetry cumbersome, as the measured magnetic fields or changes therein are detected by a magnetic field sensitive 'resistor' that converts the magnetic field information to an electrical signal. This approach typically requires physical placement of wires to the magnetic sensor element or its immediate vicinity. "Wireless" sensing offers many advantages over the conventional wired approach, but is more difficult to implement by conventional techniques. For example, in this case the telemetry may require the incorporation of a microwave transmitter as part of the sensor package. This requirement adds cost, complexity and increased power constraints to the

sensor package.

It is well known in the art that certain magneto-optic effects exist. More specifically, the Kerr effect and the Faraday effect correspond to a change in the intensity or polarization state of light either reflected from (Kerr) or transmitted through (Faraday) a magnetic material. Since the amount of change in the polarization state or intensity is proportional to the magnetisation in the material, it is possible to use these effects to examine magnetic properties of materials. However, the use of the Kerr or Faraday effects requires a light source that can be disposed to illuminate a material of interest, as well as a detector that can be disposed to receive the reflected or transmitted light. For a number of important applications these requirements can be difficult to satisfy in a cost effect and simple manner.

SUMMARY OF THE PREFERRED EMBODIMENTS

The foregoing and other problems are overcome, and other advantages are realized, in accordance with the presently preferred embodiments of these teachings.

Disclosed herein is a Magneto-Optoelectronic Device (MOD) in which a magnetic sensing device (such as a magnetoresistive device or a MTJ device) is combined with a semiconductor light emitter (such as a LED or a laser diode) to create a compact integrated device where changes in an ambient magnetic field (i.e., a magnetic field in the vicinity of the MOD) are expressed as changes in an optical beam intensity emanating from the MOD. Using the MOD the magnetic field related information can be transmitted by a light wave over very large distances through, for example, free space and/or through an optical fiber.

In one embodiment this invention provides a light source for generating light that has an intensity that varies as a function of a strength of an ambient magnetic field. The light source includes an electrical resistance that varies as a function of the strength of the ambient magnetic field, and the electrical resistance is electrically coupled in series with a light emitter. The light source forms a part of a magnetic field sensor.

In another embodiment the invention provides a method for sensing a magnetic field. The method includes (a) generating light that has an intensity that varies as a function of a strength of a magnetic field; (b) detecting the light and (c) correlating the intensity of the detected light with the strength of the magnetic field. The step of sensing can be used to detect the presence or absence of the magnetic field.

In at least one embodiment the magnetic field may be indicative of information, and the methods and apparatus can be used to detect, readout and/or transmit information.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other aspects of these teachings are made more evident in the following Detailed Description of the Preferred Embodiments, when read in conjunction with the attached Drawing Figures, wherein:

Fig. 1A is simplified schematic diagram of the hybrid Magneto-Optoelectronic Device (MOD) that is constructed to include a MTJ and a diode laser;

Fig. 1B is a graph illustrating the current/voltage characteristics of the MTJ and diode laser devices of Fig. 1A;

Fig. 2 is a graph illustrating the combined current/voltage characteristics of the MTJ and diode laser devices of Fig. 1A, as well as the light output of the diode laser device and a load line solution to an equivalent circuit;

Fig. 3 is an enlarged cross-sectional view of a first embodiment of a combined VCSEL and MTJ MOD, fabricated so as to be integrated as two epitaxially layered stacks and interconnected via a common conductive substrate;

Fig. 4 is an enlarged cross-sectional view of a second embodiment of a combined VCSEL and MTJ MOD fabricated so as to be monolithically integrated as one epitaxially layered stack,

Figs. 5A and 5B are graphs of the hybrid MOD, where Fig. 5A shows the measured electrical resistance of the MTJ component as a function of applied magnetic field, for the case of a 40X40 square micron junction; and Fig. 5B shows the output power of the VCSEL as a function of the applied magnetic field;

Fig. 6 is a circuit diagram of the combined VCSEL and MTJ MOD of Figs. 1, 3 or 4, in combination with a remote photodetector and a lock-in amplifier for receiving the modulated optical signal from the MOD;

Figs. 7A and 7B illustrate the construction and operational principles of the MTJ;

Fig. 8 is a graph illustrating VCSEL characteristics assuming a case of a 3 micron effective optical aperture, a TEM_{00} GaAs quantum well (QW) active medium, and further shows two circuit bias points of the MOD;

Figs. 9A and 9B are graphs showing the VCSEL output power (arbitrary units) versus wavelength for the same voltage (1.83 V) and for H<-100 Oe and H>100 Oe, respectively, for an embodiment where two MTJs are connected in series, as shown in Fig. 9C;

Fig. 10 shows VCSEL-based magnetic field detection operated in a differential mode, and plots a sinusoidally varying magnetic field and the resulting first derivative of the light output from the VCSEL;

Fig. 11 is an enlarged elevational view of an exemplary 4X3 two dimensional array of the monolithic MODs of a type shown in Fig. 4; and

Fig. 12 is a simplified block diagram of a system for transmitting information, the system including an information source 52 expressing information as a time varying magnetic field and at least one of the MODs.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to Fig. 1A, in accordance with the teachings of this invention an improved magnetic field sensor, also referred to herein as a hybrid Magneto-Optoelectronic Device (MOD) 10, is created by combining a thin film magneto-electronic device 12 with a compact semiconductor-based light source 14. The resulting improved magnetic field sensor 10 is preferably constructed as an integrated hybrid device where changes in the magnetic field sensed by the magnetic field sensing component 12 of the MOD 10 are translated into changes in the intensity of light emanating from the source 14. The changes in the optical intensity may be registered remotely from the MOD 10 by the use of conventional optical measurement techniques. In Fig. 1A the magneto-electronic device 12 is depicted as a magnetic field dependent resistor, and the light source 14, such as a LED or a diode laser, as a simple diode. Note that the circuit is a simple series circuit with the magneto-electronic device 12 and the light source 14 connected in series with a power supply, shown schematically as a battery 16. As is evident, a change in the resistance of the magneto-electronic device 12 due to a change in a sensed magnetic field translates into a change in the current flow through the light source 14, which in turn translates into a change in the intensity of the light output from the light source 14. In this manner a change in the strength of the magnetic field sensed by the magneto-electronic device 12 causes a modulation of the light output of the light source 14.

That is, the MOD 10 transduces a change in a magnetic field to a change in an optical output signal, which may then be propagated over large distances through free space and/or through an optical fiber.

The magneto-electronic component 12 of the MOD 10 may be based on a magnetoresistive sensor whose resistance is subject to change with changes in a magnetic field. The magnetoresistive sensor can comprise uniform thin films of suitable magnetic materials, as well as their heterostructure multilayers, where so-called "giant magnetoresistive (GMR) effects" have been found and exploited. Reference in this regard can be had, for example, to P. Grunberg, "Layered Magnetic Structures: History, Highlights, Applications", Physics Today 54, 31 (2001). In the presently preferred, but non-limiting, embodiment of this invention the magneto-electronic component 12 of the

MOD10 is embodied as a magnetic tunnel junction (MTJ). The MTJ is an example of a specific heterostructure in which a large change of resistance can be induced by changes in an external magnetic field. Reference with regard to the fabrication and operation of a MTJ can be had to the following exemplary publications: J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, "Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions", Phys. Rev. Lett. 74, 3273-3276 (1995); W. J. Gallagher, S. S. P. Parkin, Yu Lu, X. P. Bian, A. Marley, K. P. Roche, R. A. Altman, S. A. Rishton, C. Jahnes, T. M. Shaw, and G. Xiao, "Microstructured magnetic tunnel junctions", J. Appl. Phys. 81, 3741-3746 (1997); and E. Y. Chen, R. Whig, J. M. Slaughter, D. Cronk, J. Goggin, G. Steiner, and S. Tehrani, "Comparison of oxidation methods for magnetic tunnel junction material", J. Appl. Phys. 87, 6061-6063 (2000), incorporated by reference herein in their entireties.

Referring to Figs. 7A and 7B, the construction and operational principles of the MTJ 12 are shown. The MTJ 12 includes ferromagnetic (FM) layers 12B that surround a tunnel barrier layer 12A, and an anti-ferromagnetic (AF) layer 12C that functions a pinning layer. Typical layer thicknesses and compositions are also shown in the drawing. One constraint is keep the voltage across the MTJ less than about 0.4V.

While the MTJ is presently preferred for use as the magneto-electronic component 12 of the MOD 10, other types of components may be employed. For example, any spin-valve type device may be employed as the magnetic field sensing component.

Fractional resistance changes of up to $\Delta R/R \sim 0.5$ have been obtained in Co- , CoFe or NiFe-based MTJs, as well as combinations of other magnetic alloys for magnetic fields on the order of 100 Oe. This effect has been exploited in magnetic hard drive sensors as a readout device. Development is also under way to create non-volatile random access memory chips (MRAM) by using the magnetic bistability that can be created in the resistive state of an MTJ, along the easy axis of magnetization. Reference in this regard can be had to, for example, S. Tehrani, J. Slaughter, E. Chen, M. Durlam, J. Shi, and M. DeHerrera, "Progress and Outlook for MRAM Technology", IEEE Transactions on Magnetics 35, 2814 (1999).

Fig. 1B shows the typical current voltage characteristics of each element of the circuit of Fig. 1A, connected to the common voltage supply 16 through a suitably chosen series ballast resistor (not shown). The voltage axis is representative of a typical MTJ and a GaAs-based diode laser. As is well known, a semiconductor diode laser is a threshold device where the onset of stimulated emission occurs at a set value of threshold current and voltage. The threshold voltage is approximately equal to the bandgap value for the semiconductor material, approximately 1.5 V for GaAs (~800 nm wavelength range) and ~ 1V for an InGaAs or InGaAsP laser in the 1.3-1.5 μm wavelength range.

An important aspect of the hybrid magnetic sensor 10 is that the electrical current and voltage range for the MTJ 12 and the semiconductor laser (or LED) 14 are compatible. In the case of the diode laser 14, developments in the vertical cavity surface emitting lasers (VCSEL) have led to threshold currents on the order of 0.1 mA. Fig. 2 shows the current-voltage and light output vs. voltage curves for the MTJ 12 and the diode laser 14, as well as the graphical solutions to the operation of the hybrid MOD10.

In Fig. 2 it can be seen that the load line construction sets the operating point of the hybrid MOD 10 for two different values (B_1, B_2)of the magnetic field (B). In particular, for one value of the magnetic field (B_1), the resistance of the MTJ is such that the current flowing through the circuit is below the threshold of the laser 14. For a different value of the magnetic field (B_2) the resistance is reduced so that current in the circuit exceeds the threshold for the diode laser 14. As a result, for a value of the magnetic field that exceeds the threshold light is emitted from the hybrid MOD 10, which can be observed and measured at an arbitrary distance from the MOD10 (see Fig. 6). The intensity of the light can be correlated with the strength of magnetic field, as is made evident in the graph of Fig. 2.

The two device components 12 and 14 are each quite compact, and can therefore be wired on a small scale integrated circuit chip with a footprint on the scale of few hundred square micrometers (or less). Fig. 3 shows a schematic illustration of the integration of the MTJ 12 and a VCSEL device as the light source 14. In this embodiment a series circuit path is formed from the +Vo power terminal 11A through the VCSEL 14, through an electrically conductive metal substrate or trace 18, and through the MTJ 12 to a circuit

ground or circuit common terminal 11B. A supporting dielectric substrate 20, such as a layer of intrinsic silicon, alumina or a ceramic material, is typically also provided. The VCSEL 16 typically comprises multi-layer mirror or reflector structures (DBR layers) 16A that contain an a multi-quantum well (MQW) active region 16B surrounded by n-type and p-type GaAs confinement layers 16C. The MTJ 12 includes the oxide tunnel barrier layer 12A surrounded by NiFe or Co FM thin film layers 12B, and the adjacent AF exchange bias (pinning) layer 12C. The various layer thicknesses, compositions and fabrication techniques for the MTJ 12 and the VCSEL 14 may be conventional in nature. The resulting enhanced compactness and robustness is particularly relevant in sensor applications, such as one encountered in the sensing head of a magnetic hard drive.

In this implementation the use of the VCSEL as the light source 14 is preferred for at two reasons: (1) the threshold currents available in a VCSEL can be at the sub-mA level, so that a value $I_{th} \sim 0.1$-0.3 mA is readily achievable; and (2) the choice of a VCSEL geometry enables the further possibility of compact, monolithic integration of the MTJ 12 and the VCSEL 14 as part of the same multilayer material arrangement.

More particularly, in the embodiment of Fig 3 the MTJ 12 and the VCSEL 14 are shown as separate, distinct devices. However, the layered geometry and planar device processing which are common to both the VCSEL 14 (and to a resonance cavity LED) and the MTJ 12 (and other thin film GMR devices) makes it possible to monolithically integrate both devices into a single multilayer stack. This embodiment is shown in Fig. 4, where typically the VCSEL 14 structure is grown first, with the top DBR mirror layer defining the substrate on which the MTJ 12 is subsequently deposited. An additional electrically conductive interlayer 22 may be first deposited on the VCSEL 14 to optimize the substrate for the MTJ 12. In this manner a truly monolithic, ultracompact integrated magneto-optoelectronic device can be created, on a submicrometer scale if desired.

In the monolithically integrated embodiment shown in Fig. 4, where the MTJ 12 is stacked atop the VCSEL (or a resonance cavity LED (RCLED)) 14 and is separated therefrom by the (optional) electrically conductive epitaxial interlayer 22, the series circuit path is formed from the +Vo terminal 11A through the MTJ 12, through the interlayer 22, through the VCSEL (or RCLED) 14, through the electrically conductive

metal substrate or trace 18, and through the MTJ 12 to the common terminal 11B. The supporting dielectric substrate 20 is typically also provided.

The resulting compactness of the embodiment of Fig. 4 may be exploited, for example, to fabricate a magnetic read head where the signal is transmitted wirelessly in the form of the laser beam from the VCSEL 14. Moreover, this embodiment may be extended to form a linear or a two-dimensional array of the MOD10 with a very high packing density. Note as well that the light source 14 could be extended to include quantum dot VCSEL technology, in addition to quantum well VCSEL technology.

As an example, Fig. 11 depicts an enlarged elevational view of an exemplary 4X3 two dimensional array 40 of the monolithic MODs.10 of a type shown in Fig. 4. The MODs 10 are all supported by a common substrate 42, and each can be operated from the same supply voltage (Vo) as shown, or a separate, isolated voltage supply may be provided to each MOD 10.

This extension of the single hybrid MOD 10 to the two-dimensional array 40 of such devices can be accomplished by microelectronic fabrication techniques, along the lines outlined above for the embodiment of Fig. 4. By patterning the individual devices and isolating them electrically, a large number of the hybrid magneto-optoelectronic device 10 can be created and operated in parallel for enhanced magnetic field sensing and/or for reading out magnetically stored information (for example from a magnetic storage disk) at very high speeds and at high densities.

In the embodiment of Fig. 3 or Fig. 4 the threshold current/voltage of the VCSEL 14, as well as its dynamic resistance, are selected to be compatible with the current-voltage constraints imposed by the MTJ 12, as was shown with regard to Fig. 2. For example, with the resistance of a small area VCSEL 14 (A~100μm) being on the order of 100 Ω, it is preferred that the resistance of the MTJ 12 be several times smaller. This is true because the GMR effect in a MTJ device is strongly voltage dependent, decreasing roughly to half of its maximum at an applied voltage ~0.4 V across the MTJ 12. With the resistance ratios, for example, of $R_{VCSEL}/R_{MTJ} \sim$ 5:1, approximately 0. 25 V is dropped across the MTJ 12 for a threshold voltage of the GaAs-based VCSEL of about 1.3 V.

Considerations of the maximum tolerable current density in turn may limit the operating range of the MTJ 12 to some fraction of one milliamp. These considerations imply that for state-of-the art MTJ devices, the effective area is preferably on the order of about 10^3 μm^2.

Fig. 8 is a graph that illustrates characteristics of the exemplary VCSEL 14, assuming a case of a 3 micron effective optical aperture and a TEM_{00} GaAs quantum well (QW) active medium. Also shown are two circuit bias points of the MOD 10.

Figs. 9A and 9B are graphs showing the output power (arbitrary units) of the VCSEL 14 versus wavelength for the same voltage (1.83 V) and for H<-100 Oe and H>100 Oe, respectively, for an embodiment where two MTJs 10 are connected in series with the VCSEL 14, as shown in Fig. 9C.

Referring now to Figs. 5A and 5B, experimental verification of the foregoing is presented for an embodiment similar to that shown for Fig. 3. A low threshold current density VCSEL 14 was used in series with a NiFe/AlOx/NiCoFe MTJ 12, both mounted on a same substrate support. Fig. 5A compares the magnetoresistive response of the MTJ 12 alone, measured by standard conductance measurements in an external magnetic field, with that obtained by measuring the VCSEL laser output power (Fig. 5B) of the MOD 10 also in a magnetic field. To dramatize the effect, the magnetic field was directed in the easy axis direction of the MTJ 12 (switching mode). The similarity of the two hysteresis curves shown in Figs. 5A and 5B illustrates how the hybrid magneto-optoelectronic device 10 faithfully translates the magnetic field response of the MTJ 12 to optical power variations in the output of the VCSEL 14. In the hard axis configuration (not shown), where the magnetoresistive effect is simply linear in the applied field, it was found that the magnetic field sensor 10 functions as a sensitive magnetic field sensor.

Fig. 10 shows VCSEL-based magnetic field detection operated in a differential mode, and plots a sinusoidally varying magnetic field and the resulting first derivative of the light output from the VCSEL 14.

This invention can be employed to implement high-speed wireless communication

between integrated circuit-scale electronic and optical circuits. This is true because the current pulses in digital and other types of integrated circuits create time-varying magnetic fields, and these time varying magnetic fields can be sensed by the hybrid MOD 10, or by an array of the MOD 10, and translated to a stream of optical pulses for remote detection and readout.

Thus, it can be appreciated that an aspect of this invention provides a method for transmitting information, and includes (a) expressing information as a time varying magnetic field; (b) generating light that has an intensity that varies as a function of a strength of the time varying magnetic field; (c) transmitting the light; (d) receiving the transmitted light; (e) detecting the intensity of the received light and (f) obtaining the information from the detected intensity.

Further in this regard, Fig. 6 is a circuit diagram of the combined VCSEL and MTJ MOD 10 of Figs. 1, 3 or 4, in combination with a remote photodetector, such as a photodiode 30 and an amplifier, such as a lock-in amplifier 32. The photodiode 30 receives the modulated optical signal from the MOD 10, converts it to an electrical signal, and the electrical signal is amplified by the lock-in amplifier 32. The amplified signal may then be processed to determine the intensity of the received light. The output optical wavelength of the VCSEL 14 is assumed to be transmitted through some transport medium 34 which can be, as examples, free space, an optical fiber, an optical waveguide, and combinations thereof. Various optical components, such as lenses, beam splitters and polarizers can be disposed in the optical path between the VCSEL 14 and the photodiode 30, if desired. Also, at one or more points the optical signal may converted to an electrical signal, relayed through wiring, and subsequently converted back to an optical signal. In some embodiments the MOD 10 may be translated relative to a source of a magnetic field of interest, such as by scanning the MOD 10 and/or moving the source of the magnetic field.

Still further in this regard, and referring to Fig. 12, a system 50 for transmitting information includes an information source 52 for expressing information as a time varying magnetic field; at least one of the MODs 10 that is magnetically coupled to the information source 52 for generating light that has an intensity that varies as a function

of the strength of the time varying magnetic field; the transport medium 34, which may be any suitable means for conveying the light from the MOD 10; and a receiver 54 for receiving the conveyed light. The receiver includes the detector, such as the photodiode 30, for detecting the intensity of the received light and a circuit 56 such as, but not limited to, a data processor or a signal processor, for obtaining the information from the detected intensity. The light may be considered to be intensity modulated with the information, and the receiver circuit 56 may be considered to function as a demodulator. As non-limiting examples, the information source 52 could include at least one of a magnetic data storage medium and an integrated circuit.

While described in the context of presently preferred non-limiting embodiments of this invention, those skilled in the art should recognize that various modifications can be made to these presently preferred embodiments, and that all such modifications will fall within the scope of this invention. For example, the light emitter of the MOD 10 need not be based on a semiconductor material, as certain types of known light emitting polymer materials could be used as well.

CLAIMS

What is claimed is:

1. A light source for generating light that has an intensity that varies as a function of a strength of an ambient magnetic field.

2. A light source as in claim 1, comprising an electrical resistance that varies as a function of the strength of the ambient magnetic field, said electrical resistance being electrically coupled in series with a light emitter.

3. A light source as in claim 2, where said electrical resistance comprises a magnetoresistive device.

4. A light source as in claim 2, where said electrical resistance comprises a giant magnetoresistive device.

5. A light source as in claim 2, where said electrical resistance comprises a magnetic tunnel junction.

6. A light source as in claim 2, where said light emitter is comprised of a light emitting diode.

7. A light source as in claim 2, where said light emitter is comprised of a laser diode.

8. A light source as in claim 2, where said light emitter is comprised of a vertical cavity surface emitting laser.

9. A light source as in claim 2, where said light emitter is comprised of a resonant cavity light emitting diode.

10. A light source as in claim 2, where said electrical resistance comprises a magnetic tunnel junction (MTJ), where said light emitter is comprised of a vertical cavity surface

emitting laser (VCSEL), and where said MTJ and said VCSEL are disposed on a common substrate and are electrically coupled together in series between a power source terminal and a common terminal.

11. A light source as in claim 2, where said electrical resistance comprises a magnetic tunnel junction (MTJ), where said light emitter is comprised of a vertical cavity surface emitting laser (VCSEL), and where said MTJ and said VCSEL are disposed in a stacked manner one upon another on a substrate, and are electrically coupled together in series between a power source terminal and a common terminal.

12. A light source as in claim 11, where there are a plurality of said MTJs and said VCSELs disposed in a stacked manner one upon another on said substrate.

13. A magnetic field sensor, comprising a light source for generating light that has an intensity that varies as a function of a strength of an ambient magnetic field.

14. A magnetic field sensor as in claim 13, comprising an electrical resistance that varies as a function of the strength of the ambient magnetic field, said electrical resistance being electrically coupled in series with a light emitter.

15. A magnetic field sensor as in claim 14, where said electrical resistance comprises a magnetoresistive device.

16. A magnetic field sensor as in claim 14, where said electrical resistance comprises a giant magnetoresistive device.

17. A magnetic field sensor as in claim 14, where said electrical resistance comprises a magnetic tunnel junction.

18. A magnetic field sensor as in claim 14, where said light emitter is comprised of a light emitting diode.

19. A magnetic field sensor as in claim 14, where said light emitter is comprised of a

laser diode.

20. A magnetic field sensor as in claim 14, where said light emitter is comprised of a vertical cavity surface emitting laser.

21. A magnetic field sensor as in claim 14, where said light emitter is comprised of a resonant cavity light emitting diode.

22. A magnetic field sensor as in claim 14, where said electrical resistance comprises a magnetic tunnel junction (MTJ), where said light emitter is comprised of a vertical cavity surface emitting laser (VCSEL), and where said MTJ and said VCSEL are disposed on a common substrate and are electrically coupled together in series between a power source terminal and a common terminal.

23. A magnetic field sensor as in claim 14, where said electrical resistance comprises a magnetic tunnel junction (MTJ), where said light emitter is comprised of a vertical cavity surface emitting laser (VCSEL), and where said MTJ and said VCSEL are disposed in a stacked manner one upon another on a substrate, and are electrically coupled together in series between a power source terminal and a common terminal.

24. A magnetic field sensor as in claim 23, where there are a plurality of said MTJs and said VCSELs disposed in a stacked manner one upon another on said substrate.

25. A method for sensing a magnetic field, comprising:

generating light that has an intensity that varies as a function of a strength of a magnetic field;

detecting the light; and

correlating the intensity of the detected light with the strength of the magnetic field.

26. A method for detecting a presence of a magnetic field, comprising:

generating light that has an intensity that varies as a function of a strength of a magnetic field;

detecting the light; and

correlating the intensity of the detected light with the presence or absence of the magnetic field.

27. A method for transmitting information, comprising:

expressing information as a time varying magnetic field;

generating light that has an intensity that varies as a function of a strength of the time varying magnetic field;

transmitting the light;

receiving the transmitted light;

detecting the intensity of the received light; and

obtaining the information from the detected intensity.

28. A system for transmitting information, comprising:

an information source for expressing information as a time varying magnetic field;

a device that is magnetically coupled to said information source for generating light that has an intensity that varies as a function of a strength of the time varying magnetic field;

means for conveying the light from the device;

a receiver for receiving the conveyed light, said receiver comprising a detector for

detecting the intensity of the received light and a circuit for obtaining the information from the detected intensity.

29. A system as in claim 28, where said device comprises at least one electrical resistance that varies as a function of the strength of the magnetic field, said at least one electrical resistance being electrically coupled in series with a light emitter.

30. A system as in claim 28, where said at least one electrical resistance comprises a magnetoresistive device.

31. A system as in claim 28, where said at least one electrical resistance comprises a giant magnetoresistive device.

32. A system as in claim 28, where said at least one electrical resistance comprises a magnetic tunnel junction.

33. A system as in claim 28, where said light emitter is comprised of a light emitting diode.

34 A system as in claim 28, where said light emitter is comprised of a laser diode.

35. A system as in claim 28, where said light emitter is comprised of a vertical cavity surface emitting laser.

36. A system as in claim 28, where said light emitter is comprised of a resonant cavity light emitting diode.

37. A system as in claim 28, where said at least one electrical resistance is comprised of a magnetoresistive device, where said light emitter is comprised of a semiconductor light emitter, and where said magnetoresistive device and said semiconductor light emitter are disposed on a common substrate and are electrically coupled together in series between a power source terminal and a common terminal.

38. A system as in claim 28, where said at least one electrical resistance is comprised of a magnetoresistive device, where said light emitter is comprised of a semiconductor light emitter, and where said magnetoresistive device and said semiconductor light emitter are disposed in a stacked manner one upon another and are electrically coupled together in series between a power source terminal and a common terminal.

39. A system as in claim 28, where said at least one electrical resistance is comprised of a magnetic tunnel junction (MTJ), where said light emitter is comprised of a vertical cavity surface emitting laser (VCSEL), and where said MTJ and said VCSEL are disposed on a common substrate and are electrically coupled together in series between a power source terminal and a common terminal.

40. A system as in claim 28, where said electrical resistance comprises a magnetic tunnel junction (MTJ), where said light emitter is comprised of a vertical cavity surface emitting laser (VCSEL), and where said MTJ and said VCSEL are disposed in a stacked manner one upon another, and are electrically coupled together in series between a power source terminal and a common terminal.

41. A system as in claim 40, where there are a plurality of said MTJs and said VCSELs disposed in a stacked manner one upon another on said substrate.

42. A system as in claim 28, where said conveying means comprises at least one of free space, an optical fiber and an optical waveguide.

43. A system as in claim 28, where said information source comprises a magnetic data storage medium.

44. A system as in claim 28, where said information source comprises an integrated circuit.

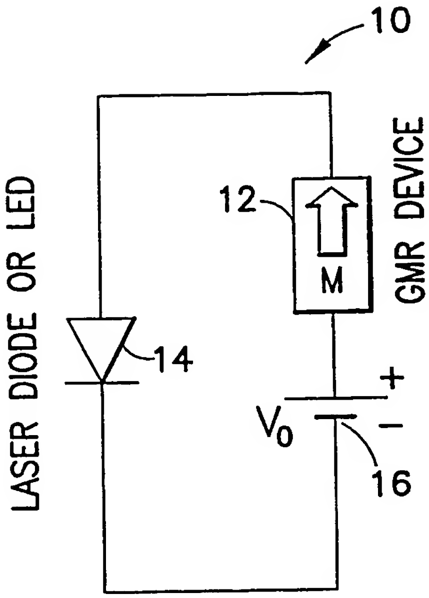


FIG.1A

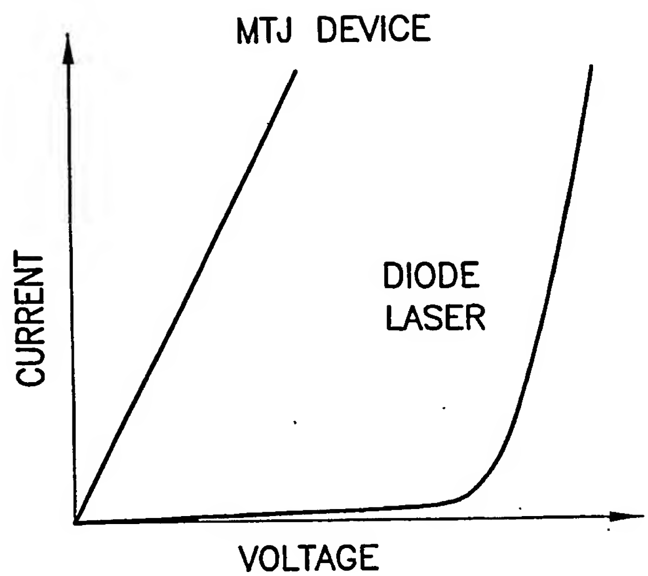


FIG.1B

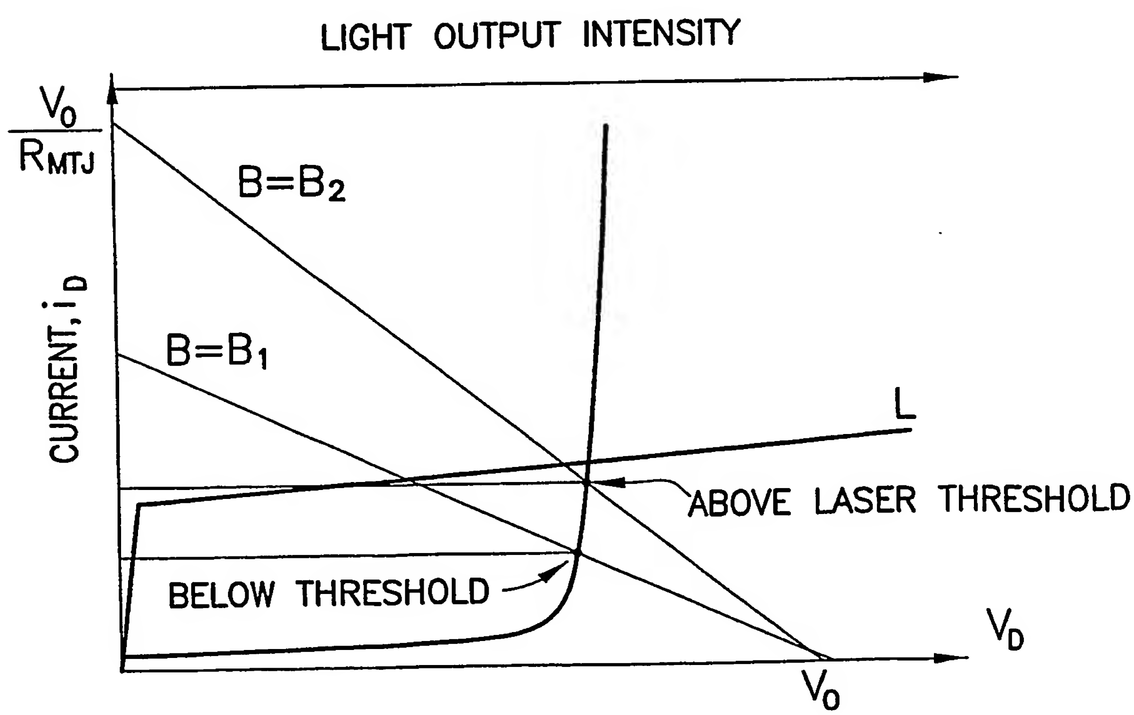


FIG.2

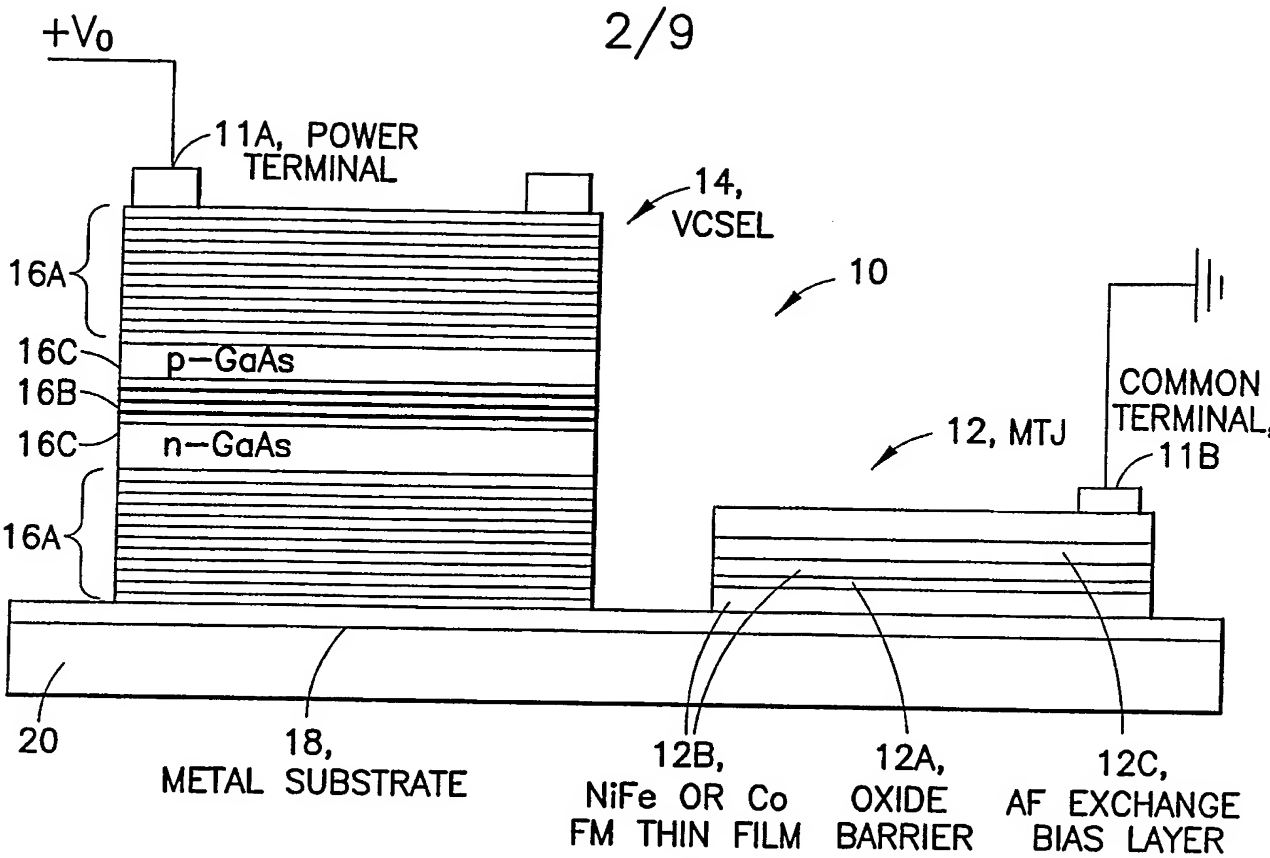

+Vo
11A, POWER TERMINAL
14, VCSEL
10
16A
16C
p-GaAs
16B
16C
n-GaAs
16A
COMMON TERMINAL, 11B
12, MTJ
20
18, METAL SUBSTRATE
12B, NiFe OR Co FM THIN FILM
12A, OXIDE BARRIER
12C, AF EXCHANGE BIAS LAYER

FIG.3

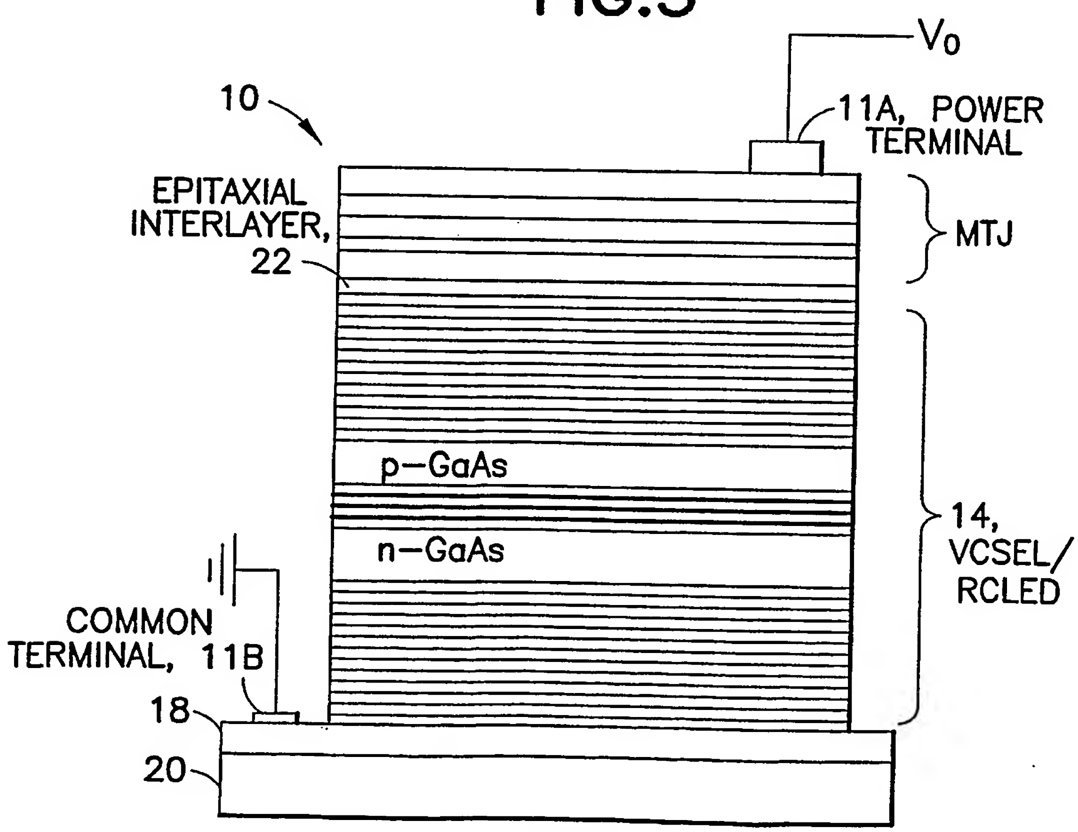

Vo
10
11A, POWER TERMINAL
EPITAXIAL INTERLAYER, 22
MTJ
p-GaAs
n-GaAs
14, VCSEL/ RCLED
COMMON TERMINAL, 11B
18
20

FIG.4

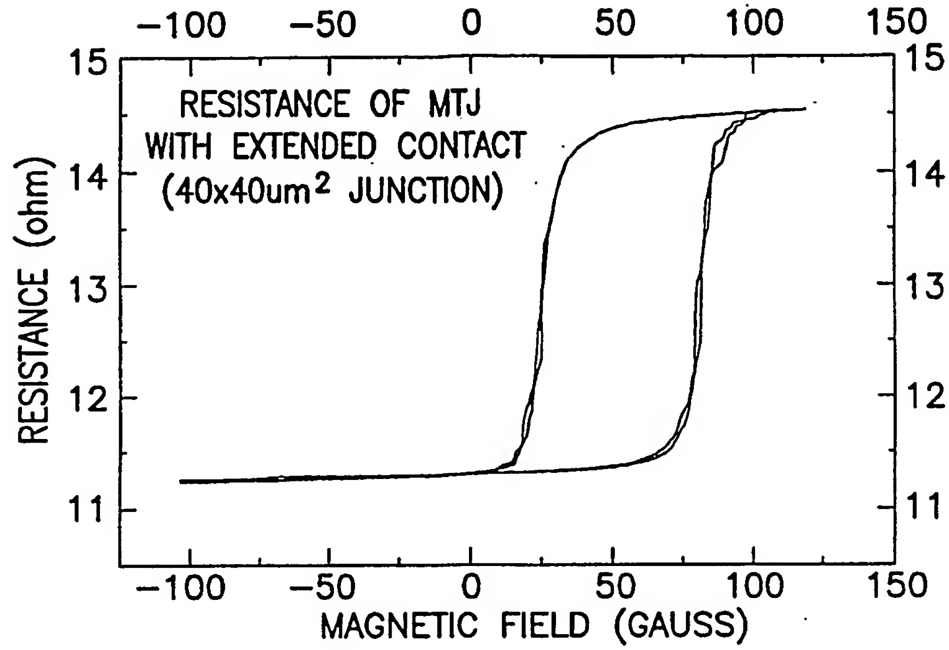

RESISTANCE OF MTJ
WITH EXTENDED CONTACT
($40x40um^2$ JUNCTION)
RESISTANCE (ohm)
MAGNETIC FIELD (GAUSS)
-100
-50
0
50
100
150
15
14
13
12
11

FIG.5A

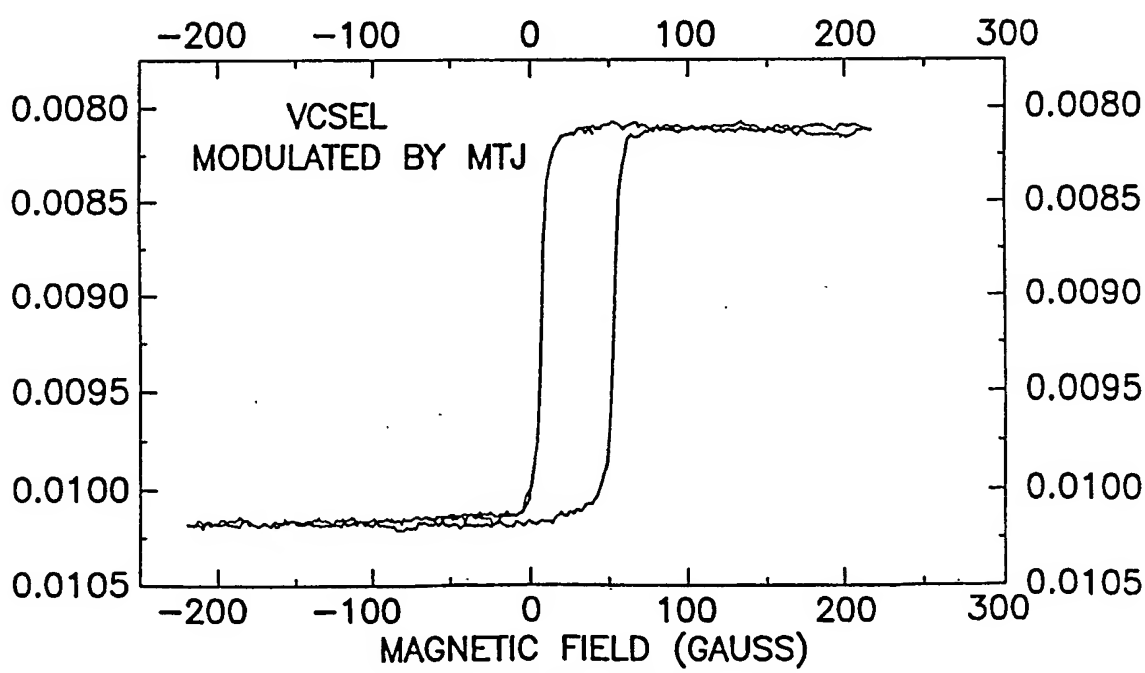
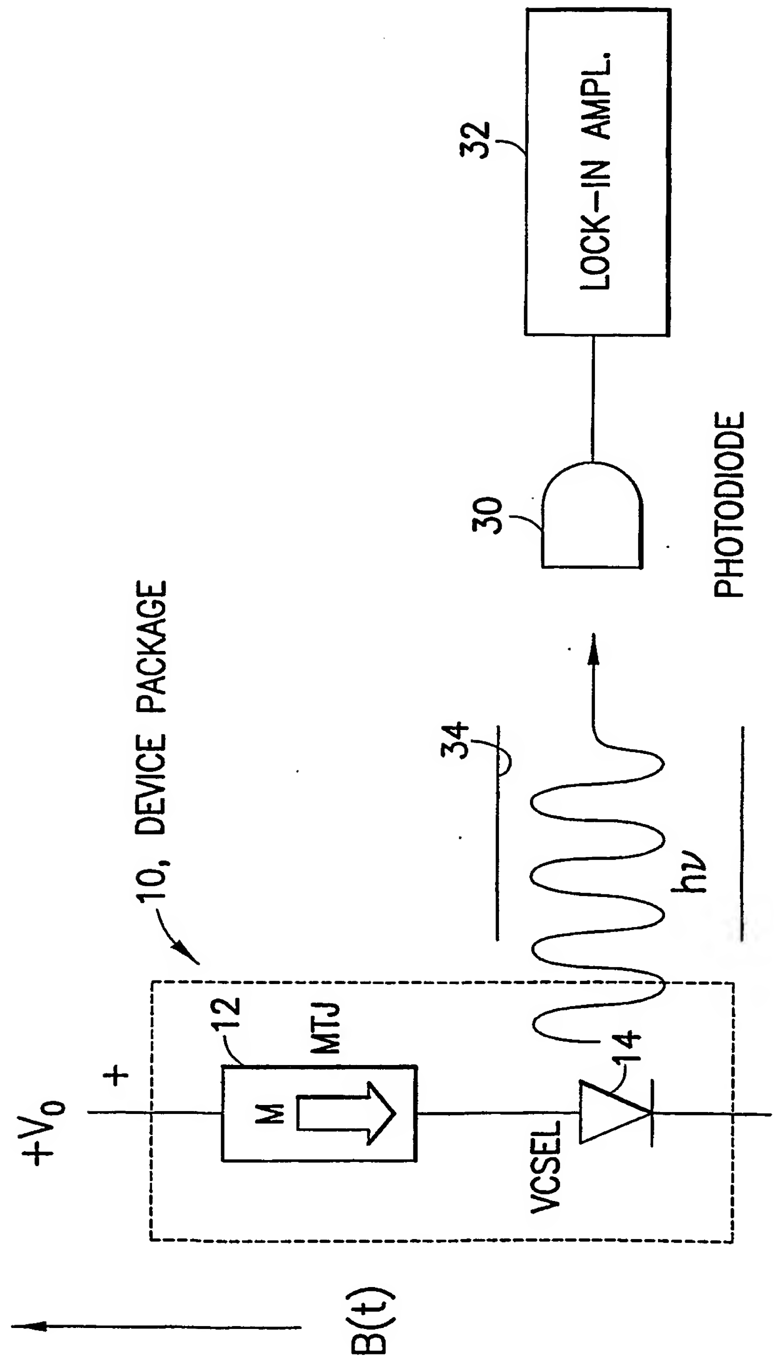

VCSEL
MODULATED BY MTJ
MAGNETIC FIELD (GAUSS)
-200
-100
0
100
200
300
0.0080
0.0085
0.0090
0.0095
0.0100
0.0105

FIG.5B



P_{VCSEL}~3mW; R_{MTJ}~10Ω; ΔR_{MTJ}~3Ω; R_{VCSEL}~300Ω,1–2mA

FIG.6

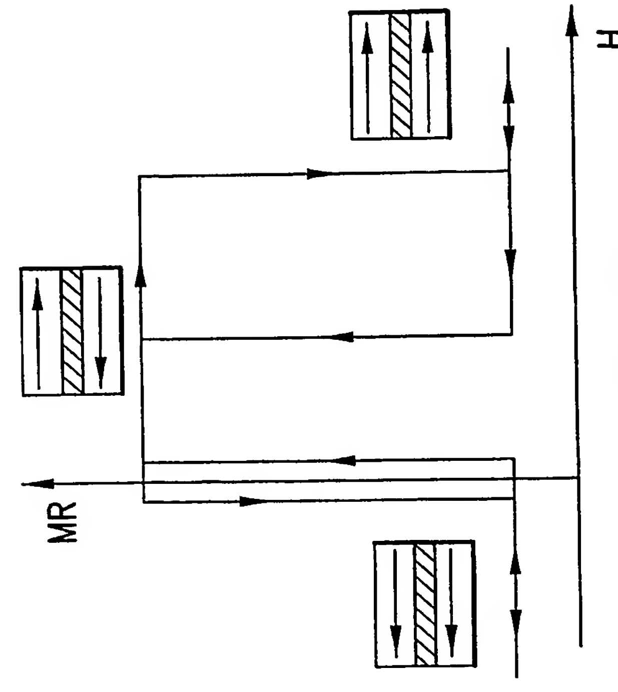


FIG.7B

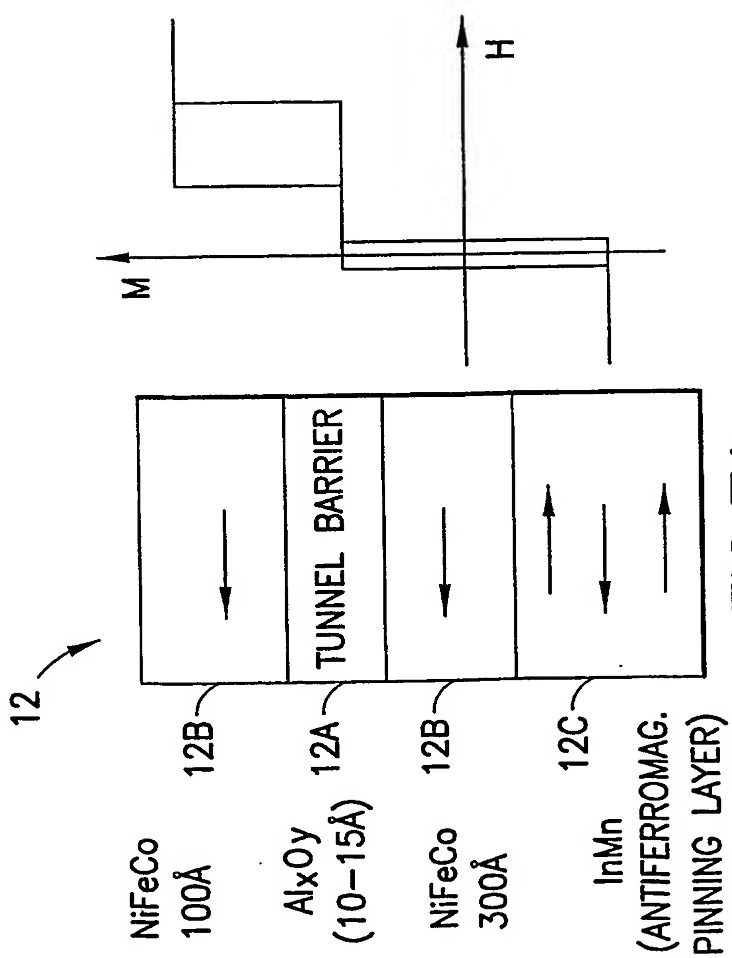


FIG.7A

–TYPICAL CHOICE OF FM LAYERS: NiFe, NiCoFe (~50–100Å)
–TYPICAL CHOICE OF PINNING AF LAYERS: NiO, FeMn, IrMn (~100Å)

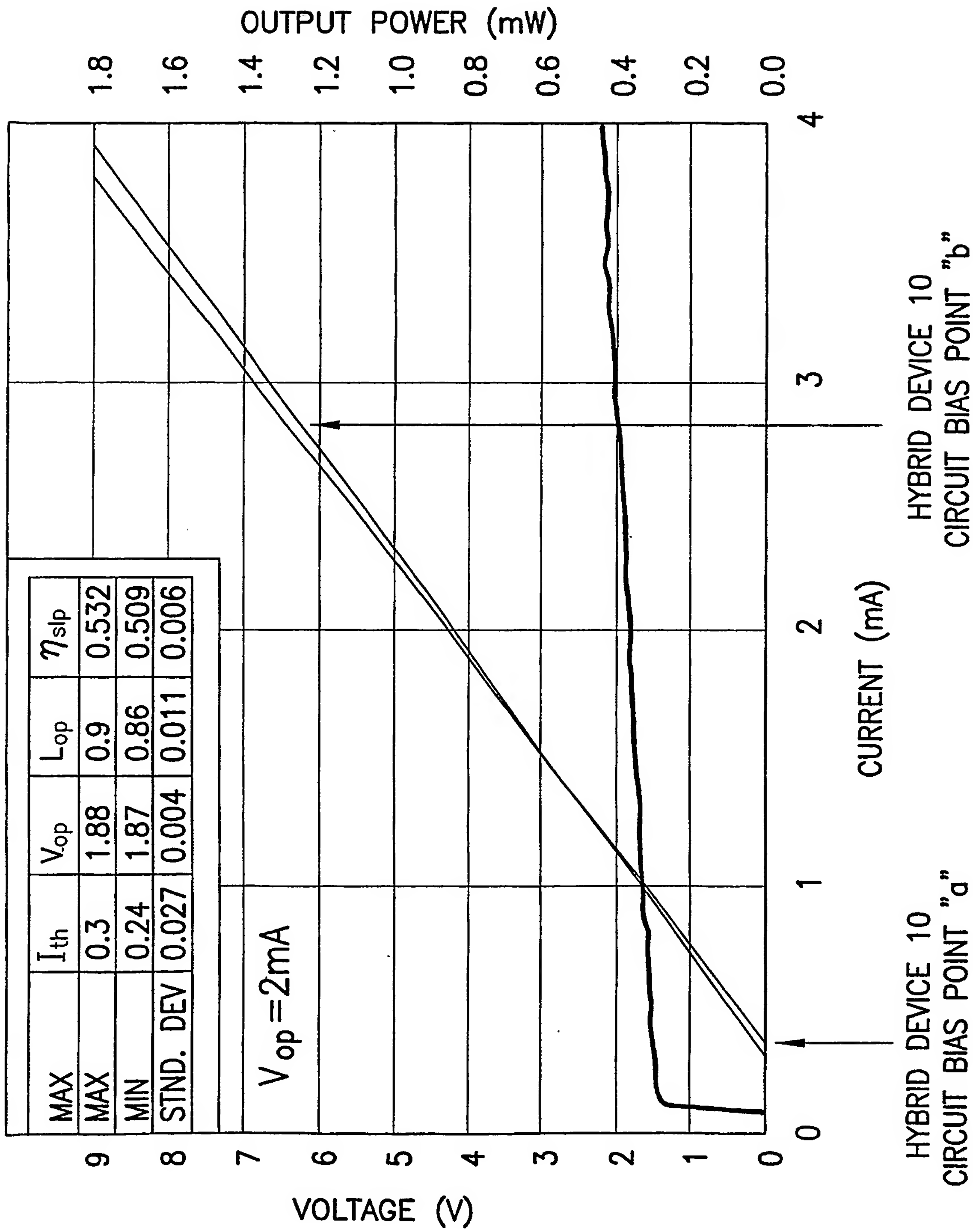

OUTPUT POWER (mW)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
VOLTAGE (V)
9
8
7
6
5
4
3
2
1
0
CURRENT (mA)
0
1
2
3
4
MAX | I_{th} | V_{op} | L_{op} | η_{slp}
MAX | 0.3 | 1.88 | 0.9 | 0.532
MIN | 0.24 | 1.87 | 0.86 | 0.509
STND. DEV | 0.027 | 0.004 | 0.011 | 0.006
V_{op}=2mA
HYBRID DEVICE 10 CIRCUIT BIAS POINT "a"
HYBRID DEVICE 10 CIRCUIT BIAS POINT "b"

FIG.8

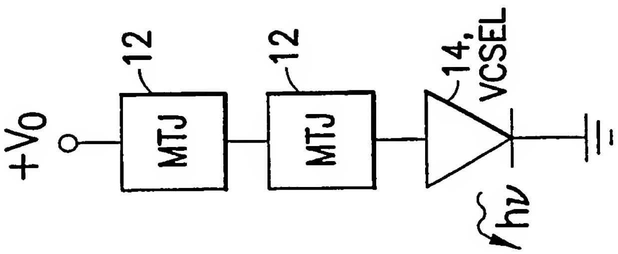


FIG.9C

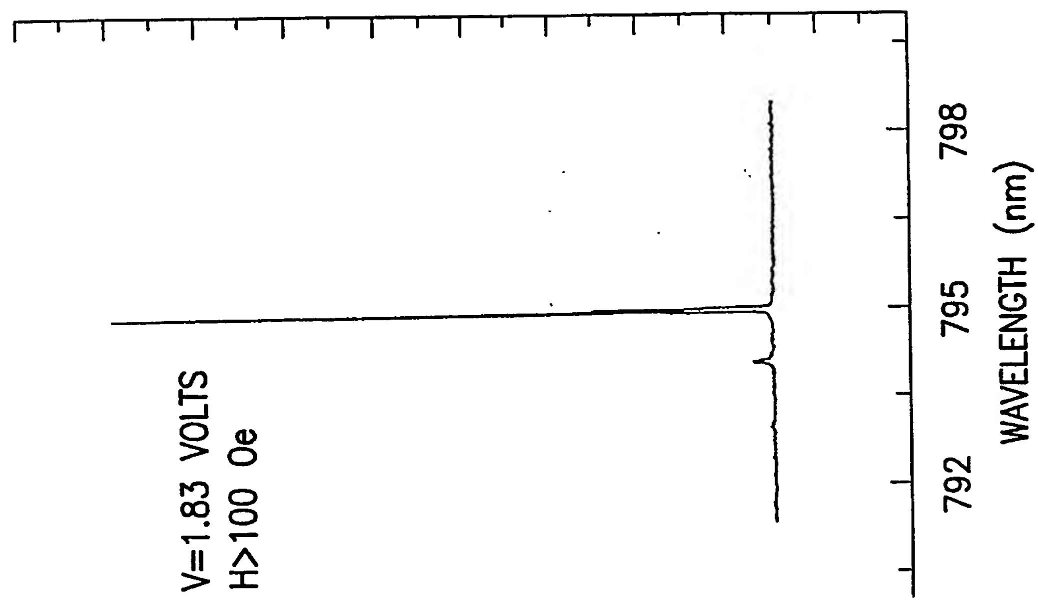


FIG.9B

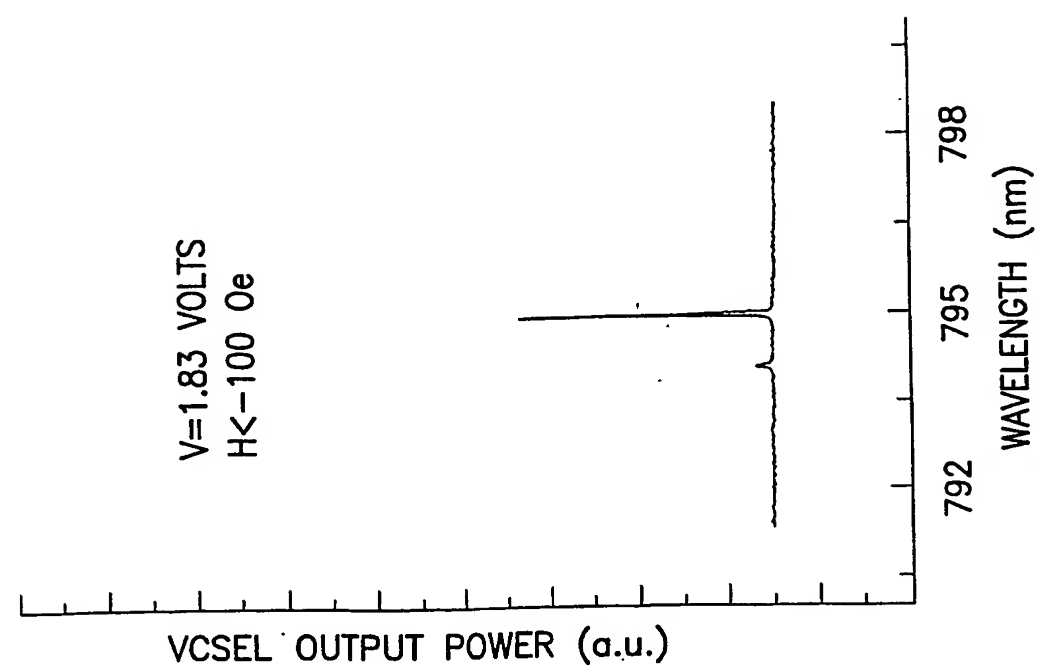


FIG.9A

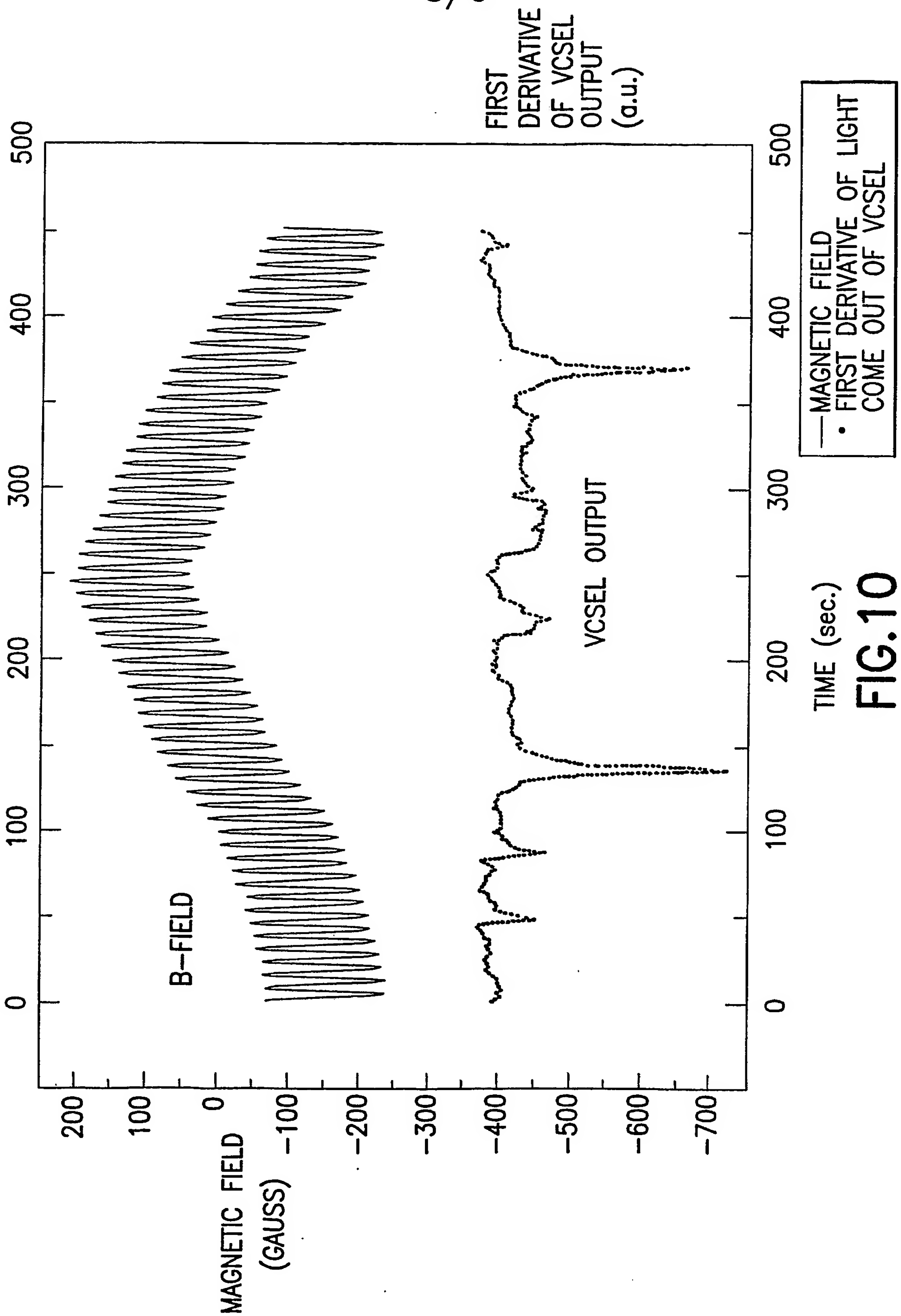

MAGNETIC FIELD (GAUSS)
200
100
0
-100
-200
-300
-400
-500
-600
-700
0
100
200
300
400
500
B-FIELD
VCSEL OUTPUT
FIRST DERIVATIVE OF VCSEL OUTPUT (a.u.)
TIME (sec.)
—MAGNETIC FIELD
• FIRST DERIVATIVE OF LIGHT COME OUT OF VCSEL

FIG.10

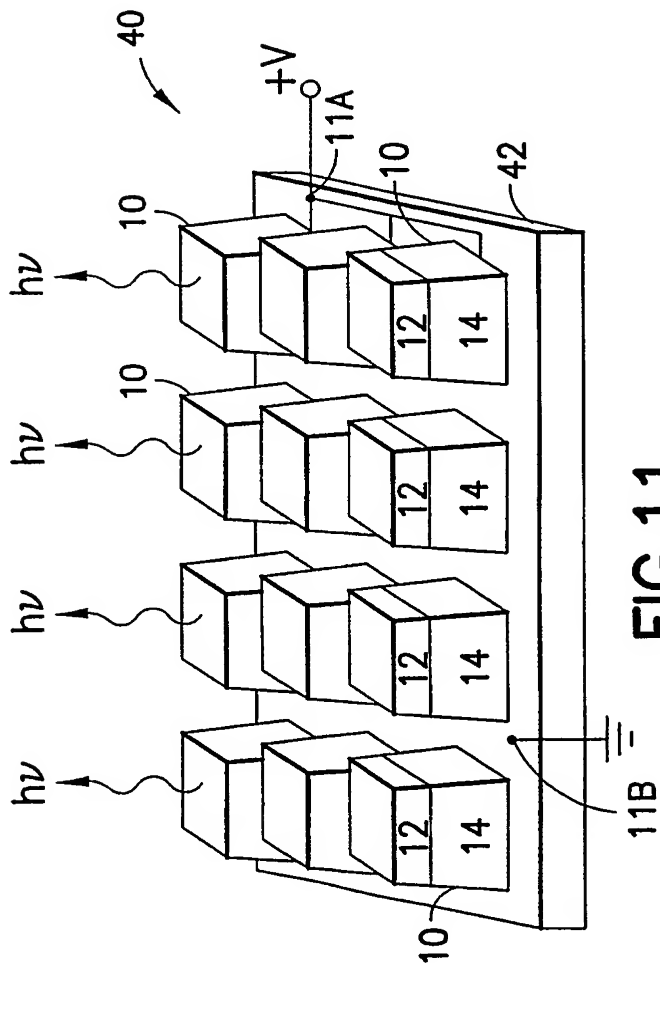

40
+V
11A
42
10
10
10
10
hν
hν
hν
hν
12
14
11B

FIG.11

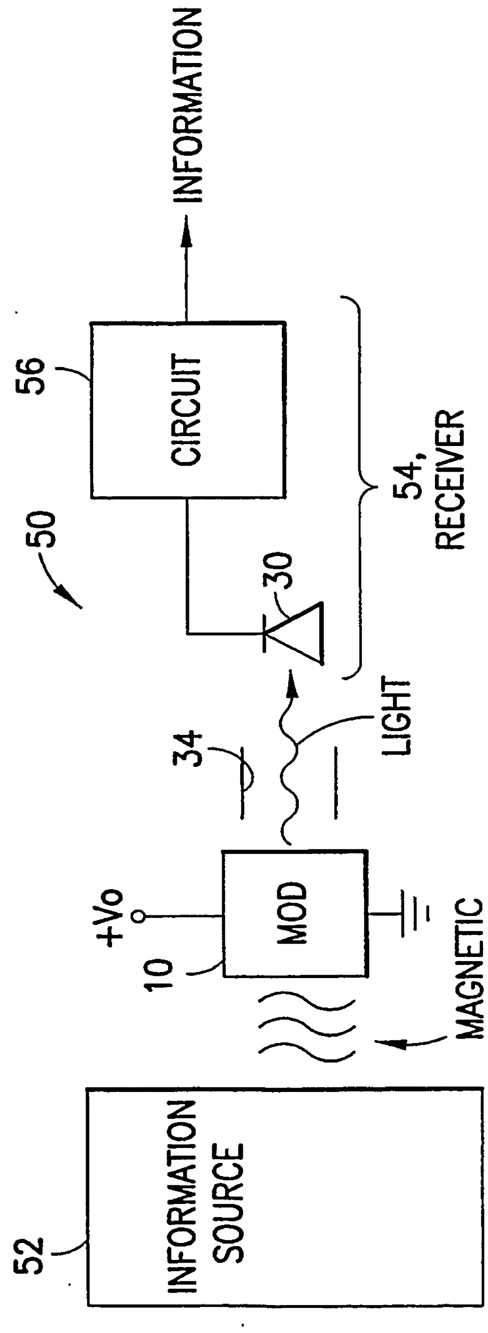

INFORMATION
56
CIRCUIT
54,
RECEIVER
50
30
LIGHT
34
+Vo
10
MOD
MAGNETIC
FIELD
52
INFORMATION
SOURCE

FIG.12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/28216

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01S 3/10, 3/082; G01B 11/02; G01R 33/02, 31/00
US CL : 372/26, 97, 356/506, 324/244, 96

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 372/26, 97, 356/506, 324/244

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Continuation Sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4,452,533 A (MILES et al) 05 June 1984 (05.06.1984), see the abstract, figure 9, and col. 5 line 25 through col. 6 line 30.	1-4, 6-7, 9, 13-16, 18-19, 21, 25-31, 33-34, 36-38, 42, 44
A	US 5,933,001 A (HUBBELL) 03 August 1999 (03.08.1999), figure 14.	1-44

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 October 2002 (23.10.2002)	12 DEC 2002

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Quyen P. Leung Telephone No. (703) 308-0956

Form PCT/ISA/210 (second sheet) (July 1998)

Continuation of B. FIELDS SEARCHED Item 3:
EAST:
magnetic tunnel junction, magnetic, sensor, vcsel, laser